Coupled Monte Carlo Neutral - Fluid Plasma Simulation

of Alcator C-Mod Divertor Plasma Near Detachment

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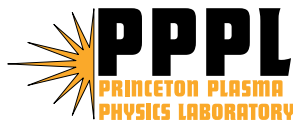
INTRODUCTION

- As n_e increased in Alcator C-Mod, divertor goes through:

    1. Low recycling,
    2. High recycling,
    3. Death Ray,
    4. Detachment.

- For last 3, $T_e < 10$ eV $\Rightarrow$ ions coupled to atoms.

    - $\Rightarrow$ Must examine both plasma and neutral transport,
    - Impurities as well.

- Death Ray (DR) pleads for kinetic treatment.

    - Defined by: p_{tot} at divertor $>$ upstream pressure.

- LaBombard (1996 PSI) suggested DR
  due to radial momentum transport by neutrals.

- Loarte (1996 PSI) said: $\perp$ viscosity.

- Here: radial transport of momentum by plasma,

    - Persists even if $\eta_\perp = 0$.

EXPERIMENTAL CONDITIONS AND SIMULATION

- Alcator C-Mod shot 950308012, $t = 0.78$ s.

- Model with B2-EIRENE,

    - B2: multi-species, 2-D fluid plasma transport,
    - EIRENE: multi-species, 3-D Monte Carlo neutral transport.

- Use SONNET to generate mesh from EFIT experimental eq'm.

- Simulations include carbon,

    - Important in power balance,
    - But not to density or momentum balance here.

- Classical $\parallel$ transport,

- Anomalous $\perp$ transport,

    - $D_\perp = 0.2$ m^{-2} s^{-1},
    - $\chi_i = \chi_e = 0.01$ m^{-2} s^{-1},
    - $\eta_\perp = 0.2$ m^{-2} s^{-1}.

- Input power: $P_e = P_i = 0.4$ MW.

- Recycling coefficient: 0.9.

- Resulting profiles:

    - n_e, T_e agree qualitatively with data,
    - Clear divertor over-pressure $\leftrightarrow$ Death Ray.

- Chord integrated D$_\alpha$ signals don't match well,

    - Have too little recombination here?
    - Divertor T_e too high?
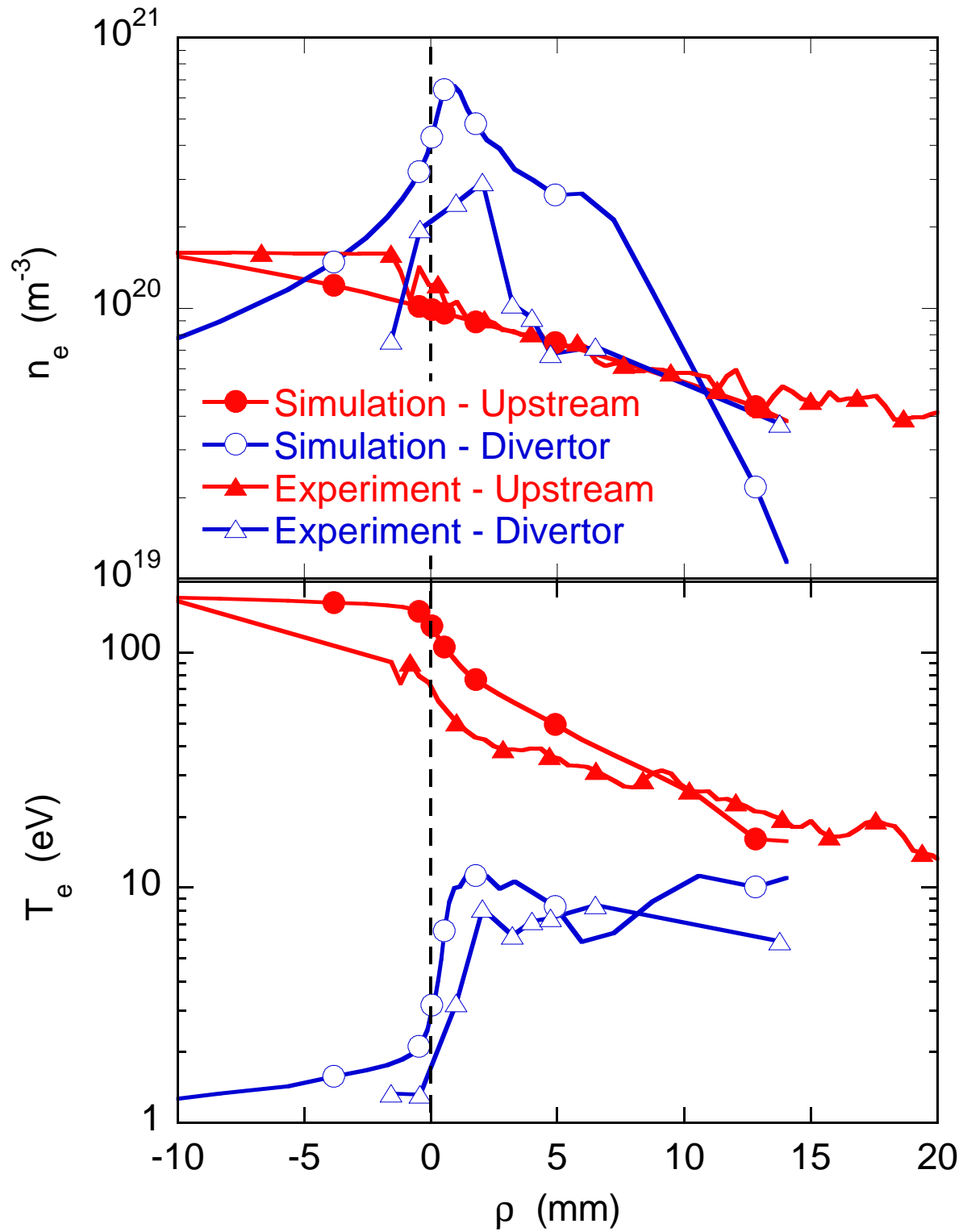   - $\Rightarrow$ seek simulations with lower T_e.

Fig. 1. Comparison of simulated and measured electron density and temperature at the outboard midplane ("upstream") and divertor.
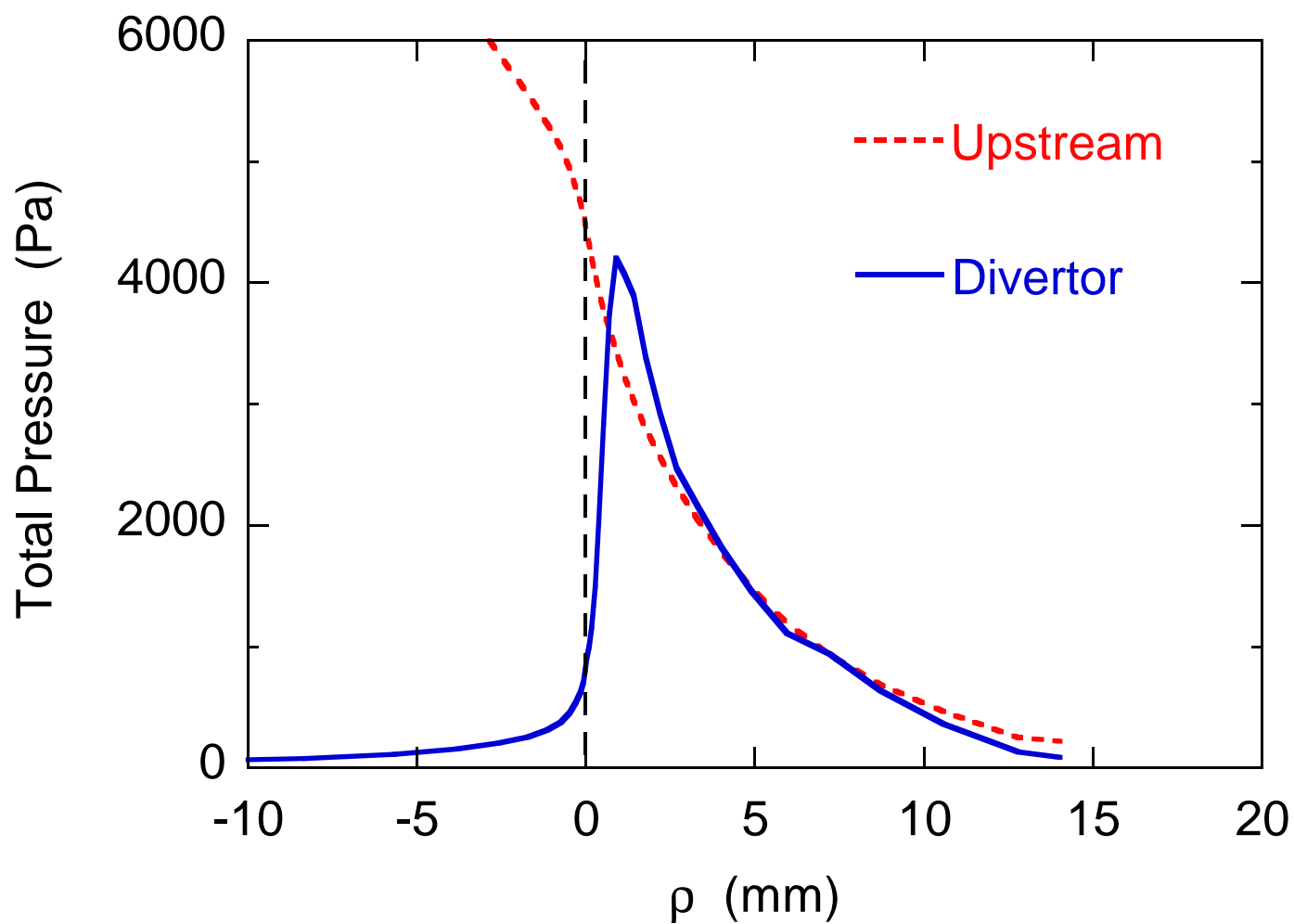
Fig. 2. Simulated total pressure (isotropic plus dynamic, summed over species) at the outboard midplane ("upstream") and divertor.
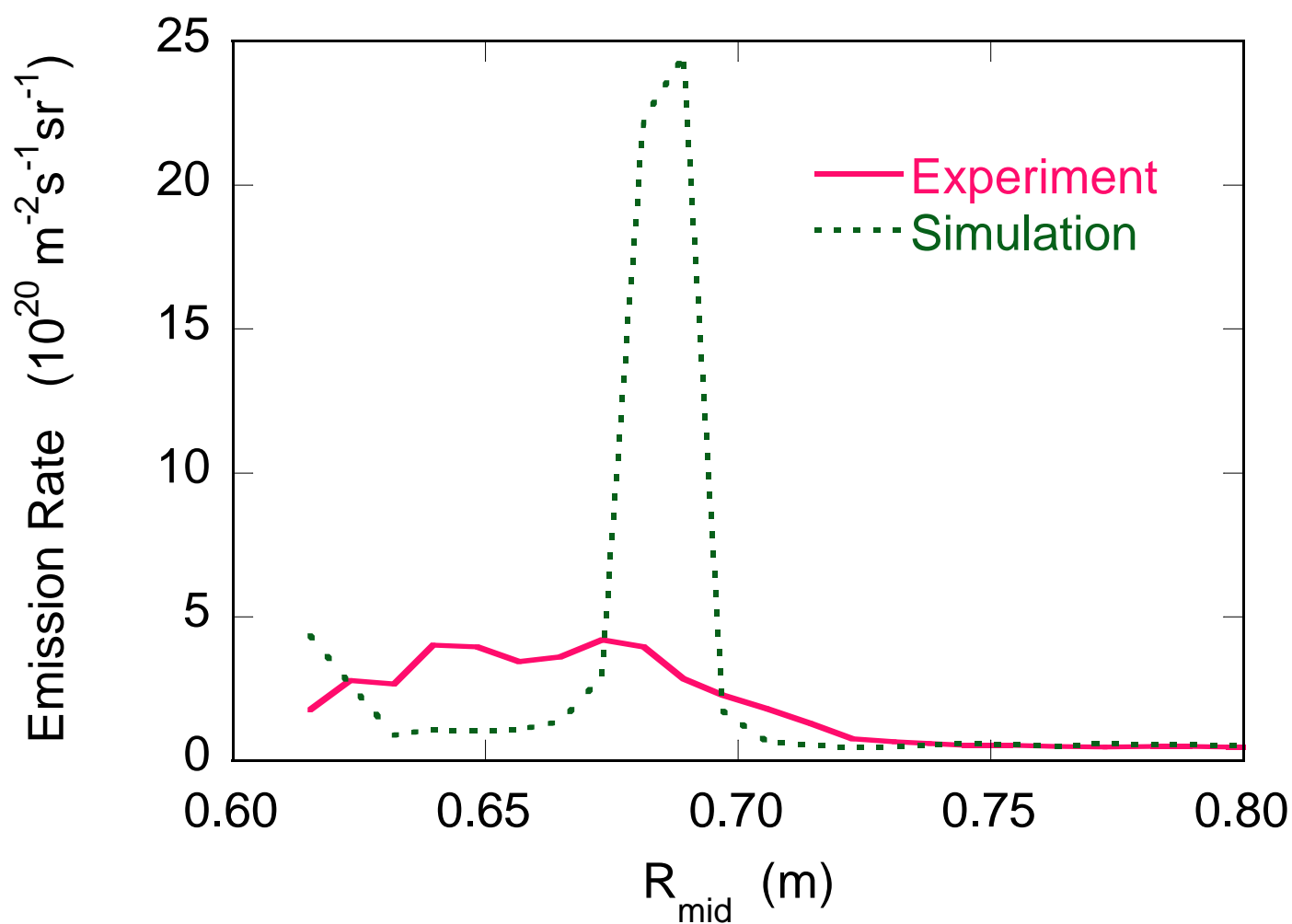
Fig. 3. Comparison of simulated and measured chord integrated D_α emission as seen by a divertor viewing detector array.

DEATH RAY INVESTIGATION

- Parallel momentum balance:

$$\frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left(\frac{\sqrt{g}}{h_x}m_a n_a u_a u_{\|,a} - \frac{\sqrt{g}}{h_x^2}\eta_{\|,a}\frac{\partial u_{\|,a}}{\partial x}\right)$$
$$+ \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left(\frac{\sqrt{g}}{h_y}m_a n_a v_a u_{\|,a} - \frac{\sqrt{g}}{h_y^2}\eta_\perp\frac{\partial u_{\|,a}}{\partial y}\right)$$
$$= \frac{B_{\text{pol}}}{B}\frac{1}{h_x}\left[-\frac{\partial p_a}{\partial x} - \frac{Z_a n_a}{n_e}\frac{\partial p_e}{\partial x}\right] + F_{\text{th}} + F_{\text{f}} + S_{mu_{\|,a}},$$

- Drop F_{th}, F_{f}.

- Ignore carbon.

- Rewrite schematically:

$$\frac{B_{\text{pol}}}{B}\frac{\partial p_{\text{tot}}}{\partial x} - \frac{\partial}{\partial x}\eta_\|\frac{\partial u_\|}{\partial x} = -\frac{\partial \Gamma_\perp}{\partial y} + S_{mu_{\|,a}}, \qquad (1)$$

- Where: $\Gamma_\perp \equiv \frac{\sqrt{g}}{h_y}m_a n_a v_a u_{\|,a} - \frac{\sqrt{g}}{h_y^2}\eta_\perp\frac{\partial u_{\|,a}}{\partial y}$,

- Without diffusion, viscosity, and neutral source $\Rightarrow p_{tot} = $ constant,

- DR $\leftrightarrow$ positive right-hand side.

- Neutral momentum source:

  – Mostly negative here,
  – $T_e \geq 10$ eV $\Rightarrow$ neutrals confined close to target,
  – $\Rightarrow$ Most high speed CX products hit wall,
  – Rest spread out.
  – Might be different if T_e lower or varied more radially.

- Radial flux:

  – DR caused by $\partial\Gamma_\perp/\partial y < 0$,
  – Occurs over same flux surfaces as DR!

DISCUSSION

- Can change $\eta_\perp$ without globally altering results,

- $\Rightarrow$ set $\eta_\perp = 0$.

- Find:

  - Virtually indistinguishable results!
  - DR moved in 0.4 mm.

- Now: $\Gamma_\perp = mnvu_\parallel$,

- Negative gradient appears connected with $\partial v/\partial y < 0$ region,

  - $v \rightarrow 0$ in some areas.
  - Corresponds to flat spot in n_e profile,
  - Seen in experimental data as well!
  - Connected with geometry, neutrals?
  - $\Rightarrow$ Study effect of geometry variations on continuity eq'n.

- Vesey (1995 APS) found DR to be ubiquitous,

- Goes away in some runs, e.g.,

  1. $P_{in} = 0.6$ MW instead of 0.8,
  2. Or, reduce recycling coeff. to 0.8.

- Look at latter case:

  - DR clearly absent,
  - Radial gradient of momentum flux positive everywhere,
  - v never vanishes,
  - No flat spot on n_e profile,
  - Because much lower atom density $\Rightarrow n_e$ closer to exponential.
  - High recycling timeslice of 950308012
    shows no flat spot in n_e either!

- Other experimental observations (LaBombard, 1996 PSI):

  - DR holds steady,
    * Same here.
  - DR moves with separatrix,
    * See ties with separatrix phenomena,
    * But, plate geometry important, too.
    * $\Rightarrow$ simulate shifted geometries.
  - DR occurs where $T_e > 6$ eV & on hottest surface,
    * $\Rightarrow$ seek simulations where this is true,
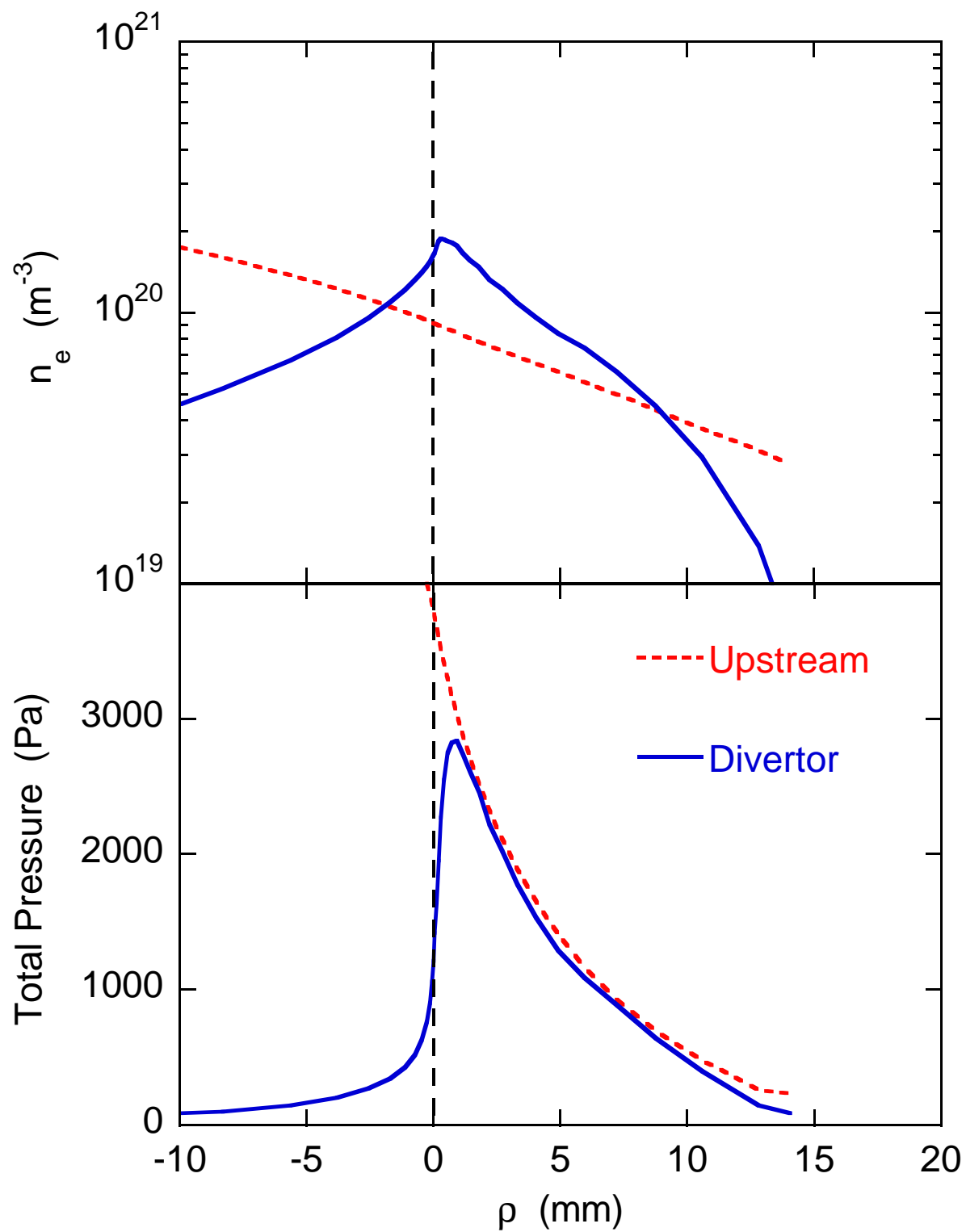   * Especially lower $T_e \Rightarrow$ more neutral.

Fig. 4. Simulated total pressure and electron density at the outboard midplane ("upstream") and divertor in a run with a recycling coefficient of 0.8.
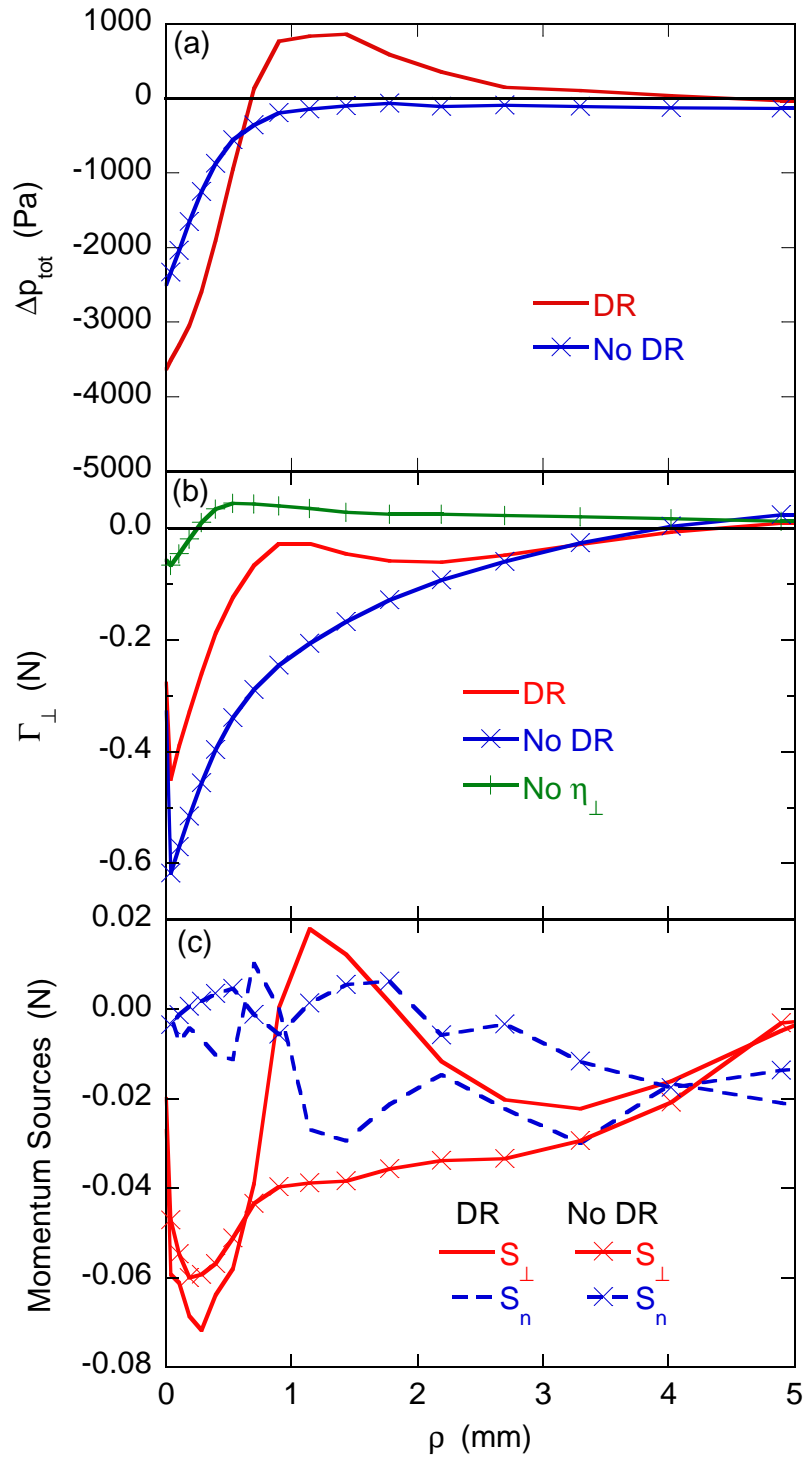
Fig. 5. Radial profiles of (a) divertor - midplane pressure difference, (b) perpendicular flux of parallel momentum, and (c) momentum sources due to perpendicular flux ($S_\perp$) and to neutrals (S_n). The values for the baseline (DR) and reduced recycling (No DR) runs are shown in each frame. The perpendicular flux from the zero viscosity (No $\eta_\perp$) run is displayed in (b).

CONCLUSIONS

- B2-EIRENE qualitatively reproduces DR conditions in C-Mod,

- Neutral transport not a signficant factor,

  - T_e too high,
  - Need simulations with lower T_e.

- Radial plasma transport of $u_\parallel$ is responsible,

  - But not just $\perp$ viscosity,
  - Connected to vanishing of radial flow,
  - And flat spot in $n_e(r)$.